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General Report Session 7: Stability of Slopes and Earth Dams Under Earthquakes

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Stability of Slopes and Earth Dams Under Earthquakes

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CLASSIFICATION OF PAPERS

The papers received for this session may be classified into five general topic areas; the number of papers in each subtopic area is shown in parentheses.

1. Slope stability analysis incorporating dynamic loading
    - analysis methods (3)
    - dynamic effects on soil properties (2)
    - case study (1)
2. Dynamic response of embankment dams
    - analysis methods (5)
    - case studies (2)
3. Dynamic deformation analysis
    - analysis methods adapted for a specific case (3)
    - comparison of analysis methods (1)
4. Dynamic deformation or stability analysis incorporating pore pressure development or liquefaction considerations
    - analysis methods (3)
    - analysis methods developed for a specific case (2)
    - case history of remediation (1)
5. Special studies
    - hillside stability monitoring system (1)
    - analysis of response of numerous dams to earthquake loading (1)

A brief synopsis of each of the papers will be provided in the order indicated above, followed by an analysis and commentary on the significance of the papers.

SLOPE STABILITY ANALYSIS INCORPORATING DYNAMIC LOADING

Analysis Methods

Matasovic develops a comparison of three seismic slope stability analysis procedures for use in evaluation of the seismic stability of a natural slope. The comparison is made by first analyzing the strength and weaknesses of each procedure, and then by using a case study to determine what would have been concluded assuming the analyses were performed in advance of the earthquake. The three methods were: the pseudostatic (or seismic coefficient) method, the Newmark (sliding block) method and the Ishihara (pseudostatic) method in which the shear strength is based on cyclic loading. The product of the first and last procedures is a factor of safety against sliding, while the product of the second procedure is a displacement that must be compared to some judgmental criteria to establish whether or not the amount of movement is significant. In the case study it turned out that all three procedures would have indicated that the slope would be just beyond a failure state. Thus, no remarkable distinction in the value of the procedures for evaluating slopes was derived from the example. The author suggests two general guides when applying the three procedures. One guide indicates under what circumstances soil properties indicate the potential for strength loss during shaking, and the second indicates under what circumstances brittle versus plastic-type failure might occur in the soil. The author suggests that the pseudostatic procedure is more applicable to the former case and that the Newmark procedure is more applicable to the second.

Basudhar, Yudhbir and **Dhawan** describe their formulation of a search routine for obtaining the critical shear surface geometry for pseudostatic dynamic slope stability analysis. The authors, in an objectively written introduction, note that the use of a seismic coefficient (pseudostatic) analysis, while widely used, is not highly regarded as an analysis technique. The authors illustrate the results of their analysis using a parametric study of the stability of an embankment dam with a thin shear plane in the dam foundation. The study revealed three important points to the authors: (1) The search program performed well in that the initial starting point had marginal influence on the final result. (2) For a given pseudostatic coefficient and given strength assumptions, the relationship between pore water pressure development and factor of safety is linear. Thus, (3) charts can be developed that show the interrelationship of various assumptions on these parameters on Factor of Safety. The authors did not provide answers to two questions that may occur to the readers while reading this paper: (1) When is it appropriate to use automated stability analysis? (2) When is it appropriate to use the "poorly regarded" pseudostatic analyses?

Koudelka develops an extension to the Method of Apriori Integration for slope stability analysis to account for earthquake effects and to account for the effect of reduced shear strength (i.e. loss of cohesion) during cyclic loading. The basic model for the slope stability analysis used in the formulation is the Swedish circular procedure. Strength reduction relations were described as a function of earthquake intensity levels. An acceleration level is also assumed as a function of earthquake intensity level. Based on these basic assumptions the mathematical solution for the critical slip surface, and its factor of safety for noncohesive and cohesive soils, is formulated. The primary result presented by the paper, other than providing the formulation of the relevant equations, is that the critical effect of the earthquake vibrations is not in the horizontal direction as is often assumed.

Dynamic Effects on Material Properties

Professor **L. J. L. Lemos** reviewed the shear strength response of soils to the rate of displacement and then explored the effects of the various responses, which varied from a strong positive rate effect to a strong negative rate effect, on the displacement patterns of old landslides and first landslides. The most important points made by the author are: (1) That granular soils have a neutral rate effect, that soils with from 5-50 percent clay fraction have a negative rate effect, and that soils with more than 50 percent clay fraction have a positive rate effect. (2) That the drop in shear resistance under rapid displacement does not appear to be related to heat or pore pressure build up but is an intrinsic property of the soil. (3) That, not surprisingly, incorporation of positive rate effects reduces displacement by an order of magnitude, and incorporation of negative rate effects predicts the observed phenomenon of landslide overshooting and coming to rest at a very stable position. (4) The model for positive rate effects also results in the possibility of a post earthquake stable condition (F.S. > 1).

Zoghi and **Bodocsi** present an investigation of the potential dynamic response of the typical colluvial hillsides in Cincinnati, Ohio, USA. The representative stratigraphy of the problem being considered is a parent bedrock consisting of interbedded shale (70 percent) and limestone (30 percent) overlain by colluvium derived from these materials. The colluvium consists of 60-90 percent illite, 10-40 percent kaolinite and minor fractions of other minerals. A thin contact zone, only a few centimeters thick, between these two zones is believed to form a major part of the slide plane. Block samples were taken from the hill side and tested in direct shear, cyclic direct shear, and post-cyclic, static direct shear. The most significant test result was that although cyclic testing did not indicate a loss in shearing resistance, the post-cyclic testing indicated a distinctly different stress-strain curve (no strong peak shear strength development). The conclusion was that earthquake loading, although not producing failure during the shaking, will cause a significant reduction in the undrained static shear strength, possibly resulting in large deformations. It was noted by the authors that in these clay materials, no excess pore water pressure development was experienced in spite of careful preparation to measure them.

Case Study

Yourman and **Diaz** present a thorough review of the geotechnical investigations that have been performed on harbor extension and protection projects in San Pedro Bay (in California, USA) over the past 30 years. The paper outlines a brief history of the various construction projects that have occurred in the harbor over this time period. Generally, they have consisted of dumping quarry waste to form underwater embankments to support hydraulic fills. The paper also outlines the various seismic studies that have been performed in the region and summarized the potentially active faults in the area. Most of the studies reached the similar conclusion that significant ground shaking can be expected in the port area within the next 50 years. The paper discusses in detail the progression of analyses performed for the bay on a decade-by-decade basis. The authors conclude that static slope stability analyses performed over the last 30 years have not changed significantly, but geotechnical analyses for seismicly induced conditions have varied substantially over this time period. Very little consideration was given to liquefaction problems in the 1960's. In the 1970's, seismic stability was analyzed using a full range of methods from finite elements to pseudostatic approaches. During the 1980's and into 1990, the analyses continued to use the pseudostatic approach uncoupled from liquefaction considerations (strength loss). However, Newmark methods were used for the first time in 1990 to obtain an estimate of actual deformations. The authors conclude that no stability analyses that allow for large permanent deformations caused by weakened soils have been performed at the site and that (2) in the past, strength loss due to pore pressure build up in the hydraulic fills and quarry wastes has not been considered and this consideration is important.

DYNAMIC RESPONSE OF EMBANKMENT DAMS

Analysis Methods

A new procedure for computing the inelastic dynamic response of an earth dam is presented by **Stara-Gazetas** and **Dobry**. The new procedure was developed in the interest of efficiency and economy. The results of the process are yielded via a dynamic analysis based on a shear beam model. However, the key to the success of the shear beam analysis is a precursor, static, finite element analysis, incrementally loaded with inertial loads, representing the earthquake loads to determine the appropriate material properties to use in the shear beam analysis. This novel approach is illustrated in the paper using a comparison with problems previously solved using commonly used dynamic response analysis techniques. A comparison of the new procedure to the equivalent linear and two dimensional finite element approach is made for the case of Lower San Fernando Dam in California, USA. Although the acceleration histories appeared very different due to differences in frequency content, the actual results for peak acceleration, peak shear stress and peak shear strain were in good agreement. The analysis of Santa Felicia Dam, California, USA, using the Provost plasticity model and finite element analysis, was used as the second basis of comparison to the shear beam model analysis. Again, the general order of magnitude of results were in good agreement; however, in this case the content of the ground motions in various elements throughout the dam were also in good agreement. The authors do not indicate superiority of the procedure in terms of final results over the current procedures but imply a more economical analysis. Data are not provided to verify that the total labor plus computer costs for this method are less than other dynamic response analysis procedures.

Dakoulas and **Hashmi** examine the effect of ground motions impacting a dam body in what they believe to be a more realistic way than commonly assumed in current analyses. Motions are applied at an angle to the foundation instead of being vertically propagating and synchronous from a common horizontal plane at the base of the dam or dam/foundation model. Applying the motion in this manner, along all three boundaries, allows consideration of the effects of reflected waves and waves that are out of phase. The authors completed a fairly extensive parametric study that allows insight on the magnitude of the effects of use of this methodology. Their findings were as follows:

1. Modeling of a flexible canyon is quite important. Dam response for the rigid canyon model, which is often used, was always greater, and may be excessively conservative.
2. The greatest response of the dam is for an angle of incidence of about 35°. (However, the difference in peak value from common practice does not appear large.)
3. For very long dams, synchronous, high frequency, excitation induces greater amplification than does asynchronous excitation.

Zaiguang and **Gao** describe their development of a seismic response analysis for dams that simultaneously considers random (nonstationary) input motion and nonlinearity of the structural response. The rationale for development of the analysis method is that more careful design, that better accounts for uncertainties, is required for modern aseismic design requirements. The analysis method is tested (demonstrated) on a sample problem, a finite element representation of a dam. Three cases are examined: stationary input and stationary output, stationary input and nonstationary output (i.e. the dam is allowed to vibrate freely upon termination of input motion), and nonstationary input and output. The comparisons show that little difference exists in the maximum acceleration or shear stress response, but that during the initial and latter portions of the 20 second motion record the response falls off sharply for the case of the nonstationary input and output case.

The first stage in dynamic analysis problems (uncoupled), whether for liquefaction evaluation or for deformation analysis, is to determine the dynamic response of the system. **Elton**, **Shie** and **Hadj-Hamou** make a comparison of the dynamic response analysis results for earth dams using SHAKE (one-dimensional) and FLUSH (two-dimensional) in order to provide guidance on when the more responsive analysis is necessary. Three variables that could influence dynamic response were examined: embankment slope, height of dam, and earthquake motion (predominant period). For the range of parameters used in the analysis, the authors concluded that these variables had little effect on results. Thus, SHAKE analyses would suffice for the cases described. The evaluation did not explore the converse problem, (i.e. under what circumstances would FLUSH be a requirement for reasons of accuracy) but suffice to say those cases do exist and can be generally described as cases where strong dynamic response of the system is anticipated. In other words, as the system becomes more flexible, the greater the need to use an analysis that is amenable to evaluating that flexibility.

In their paper on "Dynamic Response of Earth Dam - Foundation System" **Gao** and **Fei** illustrate the significant effects on response using a flexible foundation versus a rigid base via a proposed numerical procedure. This significant effect was not unexpected. The authors then used their numerical procedure and a Finite Element Model (FEM) to examine the effects of the amount of foundation modeled in a dam-foundation system subjected to earthquake loading. Their model allows or incorporates no restriction on the earthquake wave. Three earthquake motions were considered for boundaries that extend from 2-5 times dam height beyond the limits of the dam for the FEM, and to infinity for their numerical model. Although the authors indicated that "the response of the dam is not greatly affected by the truncated size in horizontal direction," it appeared from the results presented that for two of the earthquake motions the results were significantly different. The finite element results stabilized for boundaries extending four times dam height (the results for boundaries at two times dam height provided good approximations but those at three times dam height showed a variation). The authors' numerical procedures resulted in acceleration responses that were nearly 60 percent greater than the finite element results. Since the authors concluded that the results were similar for FEM boundaries greater than 3-4 times dam height, the variation was not discussed further.

Case Studies

A dynamic response analysis of Ririe Dam in Idaho, USA was reported by **Mejia**, **Sykora**, **Hynes**, **Fung** and **Koester**. State-of-the-art, two-dimensional finite element procedures (SUPERFLUSH, FEADAM) and soil property estimation methods developed by Seed and others were used in the analysis. Empirical procedures to account for three-dimensional effects were also employed. Dynamic response results from the analytical model were able to be generated for input from an actual earthquake affecting the site (1983 Borah Peak earthquake, Idaho, USA, at a distance of 179 km). The peak input motion (abutment rock) was 0.017 g and crest peak acceleration was 0.041 g. The comparison of the model results in terms of acceleration record, response spectrum, and amplification ratios was nothing short of remarkable, especially considering the small motions, the large uncertainties, and the lack of any calibration attempts. The design ground motion is 1.22 g versus the 0.017 g experienced motion. One can only postulate how well the procedures for accounting for larger strains will hold up for the design motion which is about 70 times greater than the ground motion examined in the study, but it seems promising that the effects of such small motions can be so accurately reproduced.

The paper by **Chern**, **Lee** and **Wang** illustrates a successful use of current techniques for estimating the dynamic response properties of a semihydraulic fill dam. Wushantou Dam in southern Taiwan was instrumented at the time of the November 15, 1986, Hualien earthquake. The recorded motion at the crest was used to compare and calibrate the dynamic response properties obtained by extensive field and laboratory testing. Actually little in the way of calibration was necessary as the computed properties produced an accelerogram and response spectrum which closely matched the actual record. The most significant variations of the analysis procedure used were: (1) the FLUSH program used was modified to incorporate foundation response as opposed to use of a rigid boundary, (2) the cyclic-triaxial test apparatus was modified to allow measurement at very small strains (1×10^{-6}) and, (3) down hole logging rather than crosshole was used to estimate shear wave velocity (maximum shear modulus).

DYNAMIC DEFORMATION ANALYSIS

Analysis Methods Adapted for a Specific Case

To incorporate the effect of strain history, to allow for an open hysteresis loop, and to allow for a loading condition greater than its historical maximum, **Wanhong Li** and **Wenshao Wang** propose a new nonlinear dynamic model for cohesionless soil. Stress controlled cyclic triaxial tests and ultrasonic shear wave velocity tests are used to obtain the model parameters. They use the model with modified versions of QUAD4 and FEADAM to analyze an earth dam with an underground cutoff wall. To obtain the properties for analyzing the soil/concrete interface, the authors devised a special torsional shear test. The test specimen was of two parts, one of concrete and the other of soil, with the testing occurring at the interface. With the above adaptations (plus several others) to QUAD4 and FEADAM, the response of the earth dam and foundation system were calculated for the Kern county earthquake recorded at Taft, and adjusted to a 0.15 g maximum acceleration. The cutoff was modeled as a flexible membrane and then as a beam column. The deformation results show maximum permanent displacement of the 100 M high dam to be .46 M along the downstream slope. Severe stress distribution and shear deformations occurred around the top of the concrete cutoff wall modeled as a beam column.

The numerous large earthquakes in the vicinity of La Villita Dam in Mexico since its construction in 1968 have allowed investigators an excellent empirical check on dynamic deformation analysis techniques. In recent years it was noted that the crest acceleration record contained asymmetry that could apparently be best explained by the assumption that a slip plane involving the crest existed in the dam and that this plane was unable to transmit shear forces beyond certain levels. **Succarieh**, **Yan** and **Elgamal** use the sliding block model described in another paper presented at this conference to analyze and attempt to reproduce the crest response based on this concept. Not unexpectedly, their analysis was able to reproduce the observed displacement reasonably well. The striking result which emerged from their analysis was the fact that in the absence of the sliding block hypothesis, essentially no permanent displacement at the crest would have occurred.

The computation of dynamic deformations using 2-D and 3-D FEM for the Xian-lang-de Dam were reported by **Qian**, **Zeng** and **Hong**. The authors developed specialized procedures to define dynamic stress-residual shear strain parameters and to calculate the accumulation of permanent deformation. The results for the two-dimensional analysis and three-dimensional analysis were quite comparable both horizontally and vertically. For an 8-point (Chinese scale) earthquake excitation, the permanent deformations were a little more than 1.1 percent of the 167 M dam height.

Comparison of Analysis Methods

Finite element analysis methods typically rely on a secondary (external) calculation based on indicated permanent strains to estimate the displacement of a dam exposed to seismic shaking. Rigid block analyses on the other hand typically only consider the displacement at the interface of two masses. **Succarieh**, **Elgamal** and **Lin** present a finite element model that allows for combining these two displacement modes. Their model allows for large relative displacements along predefined interaction surfaces. Geometric compatibility along the interaction surfaces is enforced by prohibiting penetration of the nodes of one mass into another. The paper illustrates the viability of the procedure via the solution of a block on an inclined plane, a slope with a known slip plane, and a back analysis of the response of La Villita Dam to the November 15, 1975, earthquake in Mexico. The concept and successful development of the procedure are intriguing. Whether the application would be limited to problems with known or suspected slip surfaces or would be practical for deformation analysis problems of a general nature, is yet to be learned.

DYNAMIC DEFORMATION OR STABILITY ANALYSIS INCORPORATING PORE PRESSURE DEVELOPMENT OR LIQUEFACTION CONSIDERATIONS

Analysis Methods

Byrne presents an effective means for estimating liquefaction induced displacements by incorporating the parameters to which the displacements are most sensitive into a simple, single degree of freedom analysis. After considering the information on observed liquefaction displacements in the field and laboratory, the empirical data on residual shear strength of flow slides and the data on post liquefaction stress-strain relationships, Byrne concludes that an appropriate displacement model can be based on the parameters of residual strength and limiting shear strain. Both of these relate strongly to $N_{1(60)}$ values. A one-dimensional liquefaction displacement model using energy considerations to control termination of displacement and a nonlinear stress-strain curve for development of post liquefaction strength is proposed. The results of analyses made for comparison with empirical data and laboratory test data show good consistency. The results of the analyses as suggested by common sense, as well as the model formulation, are strongly dependent on the $N_{1(60)}$ value obtained for the deposit. Good agreement with empirical data is obtained by estimating that the mean of the $N_{1(60)}$ is about four for ground slopes less than 4 percent. The clear, straightforward, and practical comprehensive formulation of a solution to this complex problem is reminiscent of the contributions of Dr. Seed. The method proposed by Dr. Byrne provides a foundation for making analysis of this problem reasonable and practicable.

Karaki, **Goto**, **Hirotani** and **Yoshida** review current dynamic slope stability analysis procedures and conclude that a new procedure for selecting shear strength under earthquake loading is needed. They suggest that two stability evaluation cases be routinely analyzed: (the pseudostatic case) first using the preearthquake shear strength in conjunction with a pseudostatic seismic coefficient applied to the mass, and secondly a reduced shear strength value based on post earthquake pore pressure conditions. No inertial force is applied for this case. The shear strength is selected based on an evaluation of the stress path. The shear strength suggested by the authors, for cases where large shear strain is not acceptable, is identifiable by a sharp change in curvature on the stress path. This point also corresponds to the time of maximum excess pore water pressure induced by the earthquake. The authors also suggest a new, simplified procedure for computing settlement from the earthquake shaking. The procedure consists of (1) determining the excess pore pressure ratio from response analysis, (2) use of laboratory tests in determining the change in rigidity of the soil due to the shaking, and (3) performing a finite element analysis to determine the residual deformation. The authors used the procedure on a case study that has experienced an earthquake. The case study illustrated the practicality of the methods for determining the required strength and deformation parameters for the soil. An earthquake producing a peak ground surface acceleration at the site of 0.15 g was back analyzed. Pore pressures and deformations were computed. The analysis did not indicate liquefaction occurrence (but it did show 0.75 r_u at one location). Deformation predicted by the model was 1-2 cm and maximum observed deformation was 2-5 cm.

Byrne, **Srithar**, and **Yan** present a very well described, straightforward, parametric analysis of an unusual problem related to liquefaction. The problem evaluated is the determination of the effect of pore pressures that could be generated due to liquefaction of sediments or tailings deposited or stored behind a concrete dam. It is hypothesized that higher pore pressures, due to the density of liquefied sediments, would develop under the concrete structure. Assuming the occurrence of the sediment liquefaction, the problem was evaluated in terms of pore pressure development, temporarily and spatially, for various combinations of permeability in the sediments and the foundation. If the permeability of the sediment is relatively low and the permeability of the foundation is relatively high the analysis shows significant pore pressures can develop under the structure. The pore pressure can reach even higher levels if it is assumed that the liquefied sediments can flow into the foundation. The paper illustrates that the problem can be readily solved with existing analytical tools provided that reasonable estimates of material properties can be made. The results obtained in the paper appear to be reasonable and should provide a guide to others as to whether or not a potential problem exists at a site of interest.

Analysis Methods Developed for a Specific Case

In the field of dynamic analysis of embankment dams there are two basic approaches. The coupled approach, whose development has been advanced by Dr. Finn, combines the solution of dynamic response, pore pressure development, stress development, and permanent deformation into a single problem. The decoupled approach, the development of which was advanced by Dr. Seed, separates these aspects of the problem. **Jian**, **Shiming** and **Guoxi** discuss these two methods and then opt for a coupled procedure (which they term "Effective Stress" method), in which they incorporate a pore pressure model presented by Dr. Seed. The procedure was developed in order to compare the pore pressure development indicated from analysis of two dimensional and three-dimensional models of a hypothetical dam and two tailings dams (51 meters and 120 meters high). The results of their analysis showed two major results. (1) The worst pore pressure development case occurred near the crest of an abutment section (rather than the main section) for both the hypothetical dam and for the Tonglin tailings dam, and (2) the two-dimensional analysis indicated pore pressures 10-40 percent higher in the critical zones than the three-dimensional analysis did.

Li, **Shen** and **Zhu** used an iterative procedure of static and dynamic analysis to solve the highly nonlinear problem of a potentially liquefiable fly ash deposit (wet process) retained by tailings dams. The method, although laborious, allows computation of static stability, dynamic deformation and liquefaction potential at each step of the analysis. Each step of the analysis considers a significant fraction of the earthquake record (e.g. 1/10th) versus the traditional .01 second time steps. To evaluate the effects of proposed remedial treatments (e.g. use of a drainage trench or vibroflotation of a portion of the deposits) the analysis is rerun. The most important point of this analysis is that empirical procedures for analysis of pore pressure development, combined with linear equivalent procedures to account for nonlinear static and dynamic soil response, have been adapted to solve a specific problem in what appears to be a realistic and reasonable manner.

Case History of Remediation

Lou, **Garner**, **Byrne** and **Marcuson** present a case history of the seismic evaluation and remedial design of a natural slope that serves as part of the reservoir impoundment of John Hart Lake in British Columbia. All aspects of this study were performed comprehensively. For example, seven different test methods were used to evaluate the shear strength of the silt deposits located beneath the potentially liquefiable sand layers. Therefore, in the interest of space, only some of the special aspects of the study and its findings will be pointed out: (1) Material property strength estimates were based on the 35th percentile value. (2) A degradation factor was used to account for the potential loss in monotonic shear strength of the silts following earthquake cyclic loading, although it is noted that there was little overall difference in strengths and three of nine tests indicated higher post-cyclic strengths. (3) The amount of post liquefaction displacement was considered in determining the remedial measure requirements. An interesting point that emerges when comparing theoretical studies to case histories is the degree of conservatism and engineering judgment used in actual cases. When dealing with a high hazard dam and material property uncertainty, sophisticated analytical methods providing "good" accuracy have far less significance in the overall problem solution than do engineering judgement decisions.

SPECIAL STUDIES

Hillside Stability Monitoring System

One of the most wonderful and remarkable successes in hillside displacement monitoring and early warning occurred in the Hubei Province of China above the Xintan village on the Yangtze (Changjiang) River. The entire village of 1300 people was evacuated shortly before the massive 3 million cubic meter slide completely destroyed the village. Just across the gorge (the Xiling Gorge) lies another threatening slope.

Zhu Ruigeng, **Xia Yaunyou**, and **Lu Wenxing** describe the comprehensive monitoring system developed for the slide mass. The monitoring system, which the authors refer to as "stereoscopic," is three-dimensional in nature. Precise, eletromagnetic surface surveys, underground monitoring in tunnels, and measurements in a vertical shaft are combined in such a manner that a displacement function of the mass can be developed. Instrumentation data from each of the systems can be individually monitored as well. The monitoring to date indicates that movement of the mass is occurring (approximately 5 mm in four months) and may be accelerating, but is still stable. Although no village lies below the rock mass, its plunge into the river could create a large, damaging wave on this heavily traveled and heavily populated waterway. The site of the proposed Three Gorges Project (Sandouping) is located 28 km away.

Analysis of Response of Numerous Dams to Earthquake Loading

Tani presents an update on the response of about 2000 irrigation dams in Japan due to earthquake shaking. The report is quite useful in that it provides an analysis of the physical characteristics of the 238 dams that were damaged in the 1983 magnitude 7.7 Nipponkai-Chubu earthquake, the nature of the damages and responses and a comparison of the responses to our current conceptions of what the response "should be." A comparison is also made to the reported response of dams in Japan to previous earthquakes. Most of the prevailing concepts of earthquake response of dams "survived" this detailed examination, but a few did not. Significant findings were:

1. Longitudinal cracking dominates over transverse cracking as a damage pattern (about 88 percent of the time only longitudinal cracks occur). When lateral cracks do occur they often (50% of the time) occur at the dam/abutment contact.
2. Upstream slope distress is twice as frequent as downstream distress.
3. As expected, the heavy damage rate was much higher for embankments made of sandy soil (10 of 215) than for embankments of clay (5 of 1258).
4. The damage rate to failure rate ratio was on the order of 25:1.
5. Most failures occurred within one hour of the earthquake as opposed to the reports of several days to more than one day reported for the Oza and Niigata earthquakes. The authors suggest that it was possible that this difference was related to post earthquake response (lowering water level).
6. The correlation of the age of the dam to damage occurrence was strong. The aging factor seems undoubtedly to have been confirmed as a factor in improving dynamic stability.
7. Fill dams designed using modern soil mechanics concepts experienced only slight damage even for loading exceeding design capacity.

COMMENTARY ON DYNAMIC STABILITY ANALYSIS PAPERS

The papers of this session reveal several interesting points and some interesting trends. First, there seems to be no lack of initiative, ingenuity and creativity in this field. The development trend seems to be to take existing methods and procedures and adapt them to the specific problem at hand, by simplification, by using parts of other procedures or by developing a new component for an existing procedure. This trend is fueled by one of two considerations: (1) technical considerations - i.e. an existing available procedure is not sensitive enough or flexible enough to handle the specific concern at a site; (2) economic considerations - the existing available procedure is more costly to use than desired. Such adaptations indicate a healthy condition, namely the adjustment of the analysis methods to the problem, as opposed to adjusting the problem to available analysis methods. This trend of modification of existing procedures is also indicative of the rapid change in our society and the adaptability need should be kept in mind when procedures are being developed.

A second observation is the disparity between the goals and objectives during development of analysis methods and the engineering approach on actual projects. The focus in the development of many methods is greater accuracy, which is certainly understandable. However, case histories seem to indicate a focus on (1) engineering judgment, which relies to a large degree on simple, empirical based methods and uses the results of analytical methods as a guide or framework of understanding, and (2) conservatism or redundancy which tend to obviate the need of a precise result from an analytical method, i.e. if there is a close call based on an analysis, action would be taken to provide additional protection. Actual studies also recognize the lack of precision in seismic loading evaluation (or analyses).

Finally a new, significant trend indicated in this suite of papers is that investigators are attempting to calculate the amount of deformation which may occur in a liquefaction event and consider this in their problem evaluation and resolution. This development is a departure from the prevalent opinion about five years ago that estimating the amount of deformation in a liquefaction event was not a practical goal. This opinion was based on our lack of field experience in these types of problems, and our limited ability to conduct laboratory cyclic testing on a truly representative in situ specimen. What has changed? I believe that the greatest change has been the focus on the relationship between standard penetration test results and post liquefaction shear strength and shear strain. Attention to this relationship has directed thinking away from liquefaction and flow failure as synonymous and as a yes/no type event.